

# Resolution to the $B \rightarrow \phi K^*$ polarization puzzle

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## Abstract

We resolve the  $B \rightarrow \phi K^*$  polarization puzzle by postulating a smaller  $B \rightarrow K^*$  form factor  $A_0 \approx 0.3$  and by adding penguin annihilation and nonfactorizable contributions from the perturbative QCD approach. If this explanation is valid, the penguin-dominated modes governed by the  $B \rightarrow K^*$  form factors, such as  $B^+ \rightarrow K^{*+} K^{*0}$  and  $B^0 \rightarrow K^{*0} \bar{K}^{*0}$ , should exhibit similar polarization fractions. Our resolution is compared with others in the literature, and experimental discrimination is proposed.

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To understand the polarization fractions of the  $B \rightarrow \phi K^*$  decays has been a challenge. Motivated by this subject, we have investigated most of the  $B \rightarrow VV$  modes, and observed that they are classified into four categories [1]. First, the  $B^0 \rightarrow (D_s^{*+}, D^{*+}, \rho^+) D^{*-}$  modes can be understood by kinematics in the heavy-quark limit, whose longitudinal polarization fractions  $R_L \sim 0.5$ ,  $0.5$ , and  $0.9$  [2, 3], respectively, follow the mass hierarchy among the  $D_s^*$ ,  $D^*$  and  $\rho$  mesons emitted from the weak vertex. Second, the  $B \rightarrow (\rho, \omega) \rho$  modes are understood by kinematics in the large-energy limit, leading to  $R_L \sim 1$  [4, 5, 6]. Applying the same estimation, we have predicted  $R_L \sim 0.7$  for the  $B^+ \rightarrow (D_s^{*+}, D^{*+}) \rho^0$  decays, which can be compared with future data. For penguin-dominated modes, such as those listed in Table 1, the polarization fractions deviate from the naive counting rules based on kinematics [7]: the annihilation contribution from the  $(S - P)(S + P)$  operators and the nonfactorizable contribution decrease  $R_L$  to about 0.75 for the pure-penguin  $B^+ \rightarrow \rho^+ K^{*0}$  decay. Adding a tree contribution,  $R_L$  of  $B^+ \rightarrow \rho^0 K^{*+}$  can go up to about 0.9 [1]. The fourth category, consisting of the puzzling  $B \rightarrow \phi K^*$  decays, is also pure-penguin, but its  $R_L \sim 0.5$  shown in Table 1 is much lower than 0.75.

| Mode                            | Pol.  | Fraction  | Belle                                | Babar                                  |
|---------------------------------|-------|-----------|--------------------------------------|--|
| $B^+ \rightarrow \phi K^{*+}$   | $R_L$ |           | $0.49 \pm 0.13 \pm 0.05$ [8]         | $0.46 \pm 0.12 \pm 0.03$ [9]           |
|                                 |       | $R_\perp$ | $0.12^{+0.11}_{-0.08} \pm 0.03$ [8]  |  |
| $B^0 \rightarrow \phi K^{*0}$   | $R_L$ |           | $0.52 \pm 0.07 \pm 0.05$ [8]         | $0.52 \pm 0.05 \pm 0.02$ [10]          |
|                                 |       | $R_\perp$ | $0.30 \pm 0.07 \pm 0.03$ [8]         | $0.22 \pm 0.05 \pm 0.02$ [10]          |
| Mode                            | Pol.  | Fraction  | Belle                                | Babar                                  |
| $B^+ \rightarrow \rho^0 K^{*+}$ | $R_L$ |           |                                      | $0.96^{+0.04}_{-0.15} \pm 0.04$ [9]    |
| $B^+ \rightarrow \rho^+ K^{*0}$ | $R_L$ |           | $0.50 \pm 0.19^{+0.05}_{-0.07}$ [11] | $0.79 \pm 0.08 \pm 0.04 \pm 0.02$ [12] |

Table 1: Polarization fractions in the penguin-dominated  $B \rightarrow VV$  decays.

It seems that the  $B \rightarrow \phi K^*$  polarizations are the only anomaly so far, and many attempts to resolve it have been proposed, which include new physics [13, 14], the annihilation contribution [15] in the framework of QCD-improved factorization (QCDF) [16], the charming penguin in soft-collinear effective theory (SCET) [17], the rescattering effect [18, 19, 20], and the  $b \rightarrow sg$  transition (the magnetic penguin) [21]. We have carefully analyzed these proposals [1]: the annihilation amplitude has to be parameterized in QCDF, and varying free parameters to fit the data can not be conclusive [22]. The charming penguin strategy, demanding many free parameters, does not help understand dynamics. Moreover, it has been argued that the charming penguin, without infrared divergences from diagrammatic calculations, should be factorizable in the current leading-power SCET formalism [1]. A similar criticism has been raised recently in [23]. The rescattering effect is based on a model-dependent analysis [24, 25], and constrained by the  $B \rightarrow \rho K^*$  data. The prediction  $R_\parallel \gg R_\perp$  for  $B \rightarrow \phi K^*$  [20],  $R_\parallel$  and  $R_\perp$  being the parallel and perpendicular polarization fractions, respectively, also contradicts the observed relation  $R_\parallel \approx R_\perp$  in Table 1. The exotic magnetic penguin is suppressed by the  $G$ -parity, and not sufficient to reduce  $R_L$  down to 0.5 [1]. However, we are not claiming a signal of new physics, since the complicated QCD dynamics in  $B \rightarrow VV$  decays has not yet been fully explored.

In this letter we shall investigate whether QCD effects can resolve the  $B \rightarrow \phi K^*$  polarization puzzle without resorting to exotic mechanism or new physics. These decays have been studied in the perturbative QCD (PQCD) approach [26, 27, 28], and the results of the branching ratios, the magnitudes of the helicity amplitudes  $A_L$ ,  $A_{\parallel}$ , and  $A_{\perp}$ , and their relative strong phases  $\phi_{\parallel}$  and  $\phi_{\perp}$  are summarized in Table 2 [7]. The normalization of these amplitudes have been chosen, such that they satisfy

$$|A_L|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1, \quad (1)$$

with  $|A_L|^2 = R_L$ ,  $|A_{\parallel}|^2 = R_{\parallel}$ , and  $|A_{\perp}|^2 = R_{\perp}$ . The first rows (I), coming only from the factorizable emission topology, correspond to the results under the factorization assumption (FA) [29]. It is obvious that the polarization fractions  $R_L \approx 0.92$  and  $R_{\parallel} \approx R_{\perp} \approx 0.04$  follow the naive counting rules,

$$R_L \sim 1 - O(m_{\phi}^2/m_B^2), \quad R_{\parallel} \sim R_{\perp} \sim O(m_{\phi}^2/m_B^2), \quad (2)$$

$m_B$  ( $m_{\phi}$ ) being the  $B$  ( $\phi$ ) meson mass.

| Mode              | Br ( $10^{-6}$ )     | $ A_L ^2$              | $ A_{\parallel} ^2$    | $ A_{\perp} ^2$        | $\phi_{\parallel}(rad.)$ | $\phi_{\perp}(rad.)$   |
|-------------------|----------------------|------------------------|------------------------|------------------------|--------------------------|------------------------|
| $\phi K^{*0}$ (I) | 14.48                | 0.923                  | 0.040                  | 0.035                  | $\pi$                    | $\pi$                  |
| (II)              | 13.25                | 0.860                  | 0.072                  | 0.063                  | 3.30                     | 3.33                   |
| (III)             | 16.80                | 0.833                  | 0.089                  | 0.078                  | 2.37                     | 2.34                   |
| (IV)              | 14.86                | 0.750                  | 0.135                  | 0.115                  | 2.55                     | 2.54                   |
| $\phi K^{*+}$ (I) | 15.45                | 0.923                  | 0.040                  | 0.035                  | $\pi$                    | $\pi$                  |
| (II)              | 14.17                | 0.860                  | 0.072                  | 0.063                  | 3.30                     | 3.33                   |
| (III)             | 17.98                | 0.830                  | 0.094                  | 0.075                  | 2.37                     | 2.34                   |
| (IV)              | 15.96                | 0.748                  | 0.133                  | 0.111                  | 2.55                     | 2.54                   |
| $\phi K^{*0}$     | $10.2^{+2.5}_{-2.1}$ | $0.59^{+0.02}_{-0.02}$ | $0.22^{+0.01}_{-0.01}$ | $0.19^{+0.01}_{-0.01}$ | $2.32^{+0.11}_{-0.13}$   | $2.31^{+0.12}_{-0.13}$ |

Table 2: (I) Without the nonfactorizable and annihilation contributions, (II) add only the nonfactorizable contribution, (III) add only the annihilation contribution, and (IV) add both the nonfactorizable and annihilation contributions. The last row is for  $A_0 = 0.28$ .

The next-to-leading-power annihilation amplitudes, mainly from the  $(S - P)(S + P)$  operators, and the nonfactorizable amplitudes bring the first rows into the fourth ones (IV) with the fractions  $R_L \approx 0.75$ . We observe from the second and third rows, (II) and (III), that these subleading corrections work toward the direction indicated by the data. It is easy to understand the sizable deviation from Eq. (2) caused by these subleading corrections, which are of  $O(m_{\phi}/m_B)$  for all the three final helicity states [7]. If they are of the same order of magnitude as and constructive to the transverse polarization amplitudes, an enhancing factor will be gained, which may be large enough to modify the counting rules numerically (note that  $m_{\phi}/m_B$  is only about 1/5). However, the total effect, as shown in Table 2, is not sufficient to lower  $R_L$  of the  $B \rightarrow \phi K^*$  decays down to around 0.5. The branching ratios in (I) and in (IV) are roughly equal, indicating that the subleading corrections decrease the longitudinal components and increase the transverse ones by roughly equal amount.

Two nice features exhibited in Table 2 are that PQCD has predicted  $R_{\parallel} \approx R_{\perp}$ , contrary to those from the rescattering effect [20], and that the relative strong phases among the helicity amplitudes are consistent with the  $B^0 \rightarrow \phi K^{*0}$  data:

$$\begin{aligned}\phi_{\parallel} &= 2.21 \pm 0.22 \pm 0.05 \text{ (rad.)} , & \phi_{\perp} &= 2.42 \pm 0.21 \pm 0.06 \text{ (rad.)} [8] , \\ \phi_{\parallel} &= 2.34_{-0.20}^{+0.23} \pm 0.05 \text{ (rad.)} , & \phi_{\perp} &= 2.47 \pm 0.25 \pm 0.05 \text{ (rad.)} [10] .\end{aligned}\quad (3)$$

The former implies that the rescattering effect may not be essential in  $B$  meson decays into two light mesons [30]. The consistency of the predicted  $\phi_{\parallel}$  and  $\phi_{\perp}$  with the data, once again, supports that the evaluation of strong phases in PQCD is reliable. Other examples include the predictions for the direct CP asymmetries in the  $B \rightarrow K^+ \pi^-$ ,  $\pi^+ \pi^-$  modes [27, 28], and the results of the  $B \rightarrow D^{(*)} \pi(\rho)$  branching ratios, which crucially depend on the strong phases of the color-suppressed amplitudes.

As emphasized above, the  $B \rightarrow \phi K^*$  polarizations are very unique, and it is difficult to find new mechanism, which affects only these modes but not others. Hence, we do not intend to propose any new mechanism or new physics to resolve the puzzle. To explain our idea, we quote the explicit expressions of the three helicity amplitudes in terms of the  $B \rightarrow K^*$  transition form factors in FA [1],

$$A_L \propto 2r_2 \epsilon_2^*(L) \cdot \epsilon_3^*(L) A_0 , \quad (4)$$

$$A_{\parallel} \propto -\sqrt{2}(1+r_2)A_1 , \quad (5)$$

$$A_{\perp} \propto -\frac{2r_2 r_3}{1+r_2} \sqrt{2[(v_2 \cdot v_3)^2 - 1]} V , \quad (6)$$

with the  $K^*$  ( $\phi$ ) meson velocity  $v_2$  ( $v_3$ ) and polarization vector  $\epsilon_2$  ( $\epsilon_3$ ),  $r_2 = m_{K^*}/m_B$  and  $r_3 = m_{\phi}/m_B$ . The form factors  $A_0$ ,  $A_1$ , and  $V$  in the standard definitions obey the symmetry relations in the large-energy limit [31, 32],

$$\frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E} A_1 = T_1 = \frac{m_B}{2E} T_2 , \quad (7)$$

$$\frac{m_{K^*}}{E} A_0 = \frac{m_B + m_{K^*}}{2E} A_1 - \frac{m_B - m_{K^*}}{m_B} A_2 , \quad (8)$$

where  $T_1$  and  $T_2$  are the form factors involved in the  $B \rightarrow K^* \gamma$  decays, and  $E$  is the  $K^*$  meson energy.

The results in Table 2 correspond to the form factors  $A_0 = 0.40$ ,  $A_1 = 0.26$  and  $V = 0.35$ . First, the  $B \rightarrow K^* \gamma$  branching ratios have constrained the form factors  $T_1 \approx T_2 \approx 0.3$  [33, 34], which are also in agreement with the lattice result [35]. Compared to the symmetry relation in Eq. (7), it is obvious that PQCD has given reasonable values of  $A_1$  and  $V$ . Second, there has not yet been any measurement, except  $B \rightarrow \phi K^*$ , which constrains  $A_0$ . The other penguin-dominated  $B \rightarrow \rho(\omega) K^*$  decays are mainly governed by the  $B \rightarrow \rho(\omega)$  form factors. Third, the PQCD predictions for the  $B \rightarrow \phi K^*$  branching ratios in Table 2 are larger than the data [36],

$$B(B^0 \rightarrow \phi K^{*0}) = (9.5 \pm 0.9) \times 10^{-6} , \quad B(B^+ \rightarrow \phi K^{*+}) = (9.7 \pm 1.5) \times 10^{-6} . \quad (9)$$

Note that the same value of  $A_0 \approx 0.40$  leads to the branching ratio about  $10 \times 10^{-6}$  for the longitudinal component in PQCD, but about  $5 \times 10^{-6}$  in QCDF [15, 37], because of the dynamical penguin

enhancement in the former [27]. The above three observations hint that the PQCD results for the transverse components of the  $B \rightarrow \phi K^*$  decays should have been reasonable, and that the longitudinal components may have been overestimated. We are then led to conjecture that a smaller  $A_0$  will resolve the puzzle, giving both lower  $R_L$  and lower branching ratios.

In PQCD, a  $B \rightarrow K^*$  form factor is written as the convolution of a hard kernel with the  $B$  meson wave function and with a set of  $K^*$  meson distribution amplitudes. Note that the form factors  $A_0$ ,  $A_1$  and  $V$  involve different sets of  $K^*$  meson distribution amplitudes: the twist-2  $\phi_{K^*}$ , and the two-parton twist-3  $\phi_{K^*}^t$  and  $\phi_{K^*}^s$  for  $A_0$ , and the twist-2  $\phi_{K^*}^T$ , and the two-parton twist-3  $\phi_{K^*}^v$  and  $\phi_{K^*}^a$  for  $A_1$  and  $V$  (the notations are referred to [7]). Our investigation indicates that the latter set of model distribution amplitudes derived from QCD sum rules [38] has been acceptable, but the former set has not. Recently, the reanalysis of  $\phi_{K^*}$ , parameterized as

$$\phi_{K^*}(x) = \frac{3f_{K^*}}{\sqrt{2N_c}}x(1-x)\left[1 + 3a_1^{K^*}(1-2x)\right], \quad (10)$$

showed that the Gegenbauer coefficient has a revised value  $a_1^{K^*} = 0.10 \pm 0.07$  [39], different from  $a_1^{K^*} = 0.19 \pm 0.05$  in [38]. That is, considering the theoretical uncertainty,  $\phi_{K^*}(x)$  could be quite close to the asymptotic model corresponding to  $a_1^{K^*} = 0$ .

To test our idea, we choose the asymptotic models for the  $K^*$  meson distribution amplitudes relevant to the evaluation of  $A_0$ :

$$\phi_{K^*}(x) = \frac{3f_{K^*}}{\sqrt{2N_c}}x(1-x), \quad (11)$$

$$\phi_{K^*}^t(x) = \frac{f_{K^*}^T}{2\sqrt{2N_c}}3(1-2x)^2, \quad (12)$$

$$\phi_{K^*}^s(x) = \frac{f_{K^*}^T}{2\sqrt{2N_c}}3(1-2x), \quad (13)$$

which lead to  $A_0 = 0.28$ , about 70% of the original value. The main reduction is caused by the change of  $\phi_{K^*}^s$  in Eq. (13). The model-dependent evaluations of  $A_0$  vary in a wide range from 0.31 to 0.47, and  $A_0 \approx 0.3$  has been supported by the recent covariant light-front QCD (LFQCD) calculation [40]. This smaller value does not contradict to any existing data as emphasized above. We suggest to also reanalyze  $\phi_{K^*}^t$  and  $\phi_{K^*}^s$  in QCD sum rules, so that it is possible to examine whether a consistency between the PQCD and LFQCD results of  $A_0$  can be achieved.

The models for the distribution amplitudes  $\phi_{K^*}^T$ ,  $\phi_{K^*}^v$  and  $\phi_{K^*}^a$ , relevant to the evaluation of the form factors  $A_1$  and  $V$ , and those for the  $\phi$  meson distribution amplitudes and for the  $B$  meson wave function, remain the same as in [7]. We then compute all amplitudes, including the penguin emission, penguin annihilation and nonfactorizable ones, for the longitudinal and transverse polarizations using the  $k_T$  factorization formulas in [7]. The numerical outcomes are listed as the last row in Table 2. Simply adopting the asymptotic models in Eqs. (11)-(13), the modified branching ratio  $10.2 \times 10^{-6}$ , the polarization fractions  $R_L = 0.59$  and  $R_{||} \approx R_{\perp}$ , and the relative strong phases  $\phi_{||} \approx \phi_{\perp} \approx 2.3$ , are all consistent with the  $B^0 \rightarrow \phi K^{*0}$  data in Table 1, and in Eqs. (3) and (9). Therefore, we claim that the measured  $B \rightarrow \phi K^*$  polarizations might imply nothing but a smaller form factor  $A_0$ , and that their explanation does not require any exotic mechanism or new physics. The penguin annihilation and nonfactorizable contributions play an important role here. In FA without these contributions,

$A_0$  has to be as small as 0.15 in order to reach  $R_L \sim 0.6$ , for which the  $B \rightarrow \phi K^*$  branching ratios will fall far below the data.

The central values in the last row of Table 2 correspond to the shape parameter  $\omega_B = 0.40$  GeV, appearing in the  $B$  meson wave function [27],

$$\phi_B(x, b) = N_B x^2 (1-x)^2 \exp \left[ -\frac{1}{2} \left( \frac{x m_B}{\omega_B} \right)^2 - \frac{\omega_B^2 b^2}{2} \right], \quad (14)$$

where the normalization constant  $N_B$  is related to the decay constant  $f_B$  through

$$\int dx \phi_B(x, b=0) = \frac{f_B}{2\sqrt{2}N_c}, \quad (15)$$

and the variable  $b$  conjugate to the parton transverse momentum in the  $B$  meson. The errors in the superscripts (subscripts) come from  $\omega_B = 0.36$  ( $\omega_B = 0.44$ ) GeV. The range  $\omega_B = 0.40 \pm 0.04$  GeV, determined by a fit to the  $B \rightarrow \pi$  form factor from light-cone sum rules [41, 42], leads to the  $B \rightarrow K^*$  form factors  $A_0 = 0.28^{+0.04}_{-0.03}$ ,  $A_1 = 0.26^{+0.04}_{-0.03}$ , and  $V = 0.35^{+0.06}_{-0.04}$ . The above theoretical errors simply mean those arising from the unknown  $B$  meson wave function. It is clear that the polarization fractions are insensitive to this source of uncertainties. There are certainly other sources of theoretical uncertainties, whose detailed investigation is not the focus of this work.

If our explanation is valid, the  $B \rightarrow \phi K^*$  decays can be classified into the same category as of  $B \rightarrow \rho K^*$ , for which the subleading penguin annihilation and nonfactorizable contributions render the polarization fractions deviate from the naive counting rules based on kinematics. The only difference is that the form factor ratio  $A_0/A_1$  for the  $B \rightarrow K^*$  transition is smaller than that for the  $B \rightarrow \rho$  transition. For example, LFQCD gave  $A_0/A_1 = 1.19$  for the former, and  $A_0/A_1 = 1.27$  for the latter [40]. PQCD, using the set of  $\rho$  meson distribution amplitudes from [38], gave  $A_0/A_1 = 1.63$  [41]. The PQCD results for the  $B \rightarrow \pi\rho$  decays, to which the  $B \rightarrow \rho$  form factors are relevant, have been in good agreement with the data [43]. It implies that the values of the  $B \rightarrow \rho$  form factors yielded in PQCD are reasonable. Therefore, the longitudinal polarization fraction  $R_L$  of the  $B^+ \rightarrow \rho^+ K^{*0}$  decay should be larger than that of  $B \rightarrow \phi K^*$ . An explicit study of the  $B \rightarrow \rho K^*$  modes in PQCD is in progress. Furthermore, if our explanation is correct, the modes governed by the  $B \rightarrow K^*$  form factors, such as  $B^+ \rightarrow K^{*+} K^{*0}$  and  $B^0 \rightarrow K^{*0} \bar{K}^{*0}$ , must have low  $R_L \approx 0.6$ . Note that the  $B \rightarrow \phi K^*$  modes occur through the  $b \rightarrow s$  penguin, while the  $B \rightarrow K^* K^*$  modes occur through the  $b \rightarrow d$  penguin. From the viewpoint of PQCD, the  $B \rightarrow \omega K^*$  decays, without exotic mechanism, show  $R_L$  close to those of  $B \rightarrow \rho^0 K^*$ . All the above predictions can be confronted with the future polarization measurement of the  $B \rightarrow K^* K^*$ ,  $\omega K^*$  decays.

At last, we compare the polarization fractions of the  $B \rightarrow \rho K^*$ ,  $\omega K^*$  decays derived from the different approaches with the  $B \rightarrow \phi K^*$  data in Table 3. The prediction from the rescattering effect [18, 19, 20] is easily understood: the  $B \rightarrow \rho K^*$ ,  $\phi K^*$  decays involve the same  $D_s^{(*)} D^{(*)}$  intermediate states, and their polarization fractions are certainly almost equal. The relation  $R_{\parallel}(\phi K^*) \gg R_{\perp}(\phi K^*)$  is attributed to the vanishing  $R_{\perp}$  in the  $B \rightarrow D_s^* D^*$  channels. The  $b \rightarrow sg$  transition contributes to the  $B \rightarrow \omega K^*$ ,  $\phi K^*$  modes, such that their polarization fractions are close to each other [21]. Without the rescattering effect, the parallel and perpendicular polarization fractions are expected to be similar. This is also the case in PQCD [7] and in QCDF [15]. The future data can provide an unambiguous discrimination among these proposals. We did not list QCDF in Table 3, because both

the relations  $R_L(\rho^+ K^{*0}) > R_L(\phi K^{*0})$  and  $R_L(\rho^+ K^{*0}) \approx R_L(\phi K^{*0})$  are allowed within the involved large theoretical uncertainty [44]. Hence, it is difficult to discriminate QCDF experimentally from the others.

|                 |  |   |
|-----------------|--|---|
| PQCD            | $R_L(\rho K^*) > R_L(\phi K^*)$<br>$R_L(\omega K^*) \approx R_L(\rho^0 K^*)$ | $R_{\parallel}(\phi K^*) \approx R_{\perp}(\phi K^*)$ |
| rescattering    | $R_L(\rho K^*) \approx R_L(\phi K^*)$  | $R_{\parallel}(\phi K^*) \gg R_{\perp}(\phi K^*)$     |
| magnetic dipole | $R_L(\omega K^*) \approx R_L(\phi K^*)$                                      | $R_{\parallel}(\phi K^*) \approx R_{\perp}(\phi K^*)$ |

Table 3: Comparison of the  $B \rightarrow \rho K^*, \omega K^*$  polarization fractions from the different proposals with the  $B \rightarrow \phi K^*$  data.

In this letter we have proposed a possible resolution to the  $B \rightarrow \phi K^*$  polarization puzzle within the Standard Model, which was found to be nothing but the consequence of a smaller  $B \rightarrow K^*$  form factor  $A_0$ . Postulating  $A_0 \approx 0.3$ , which does not contradict to any existing measurement, we are able to explain the data in the PQCD approach. This form factor value leads to  $R_L = 0.84$  in FA (smaller than 0.92 corresponding to  $A_0 = 0.40$  in Table 2). The penguin annihilation from the  $(S - P)(S + P)$  operators and the nonfactorizable contribution, which can be estimated reliably in PQCD, then further bring  $R_L$  down to 0.59. The remaining concern is whether the asymptotic models in Eqs. (11)-(13) are allowed within theoretical uncertainty. We have suggested to reanalyze these  $K^*$  meson distribution amplitudes appearing in the factorization formula for  $A_0$  in the framework of QCD sum rules. Because of the unknown  $A_0$ , which is a source of QCD uncertainty, it is still too early to claim any exotic mechanism or new physics in the  $B \rightarrow \phi K^*$  polarization data. We have predicted that the penguin-dominated decays governed by the  $B \rightarrow K^*$  form factors, such as  $B^+ \rightarrow K^{*+} K^{*0}$  and  $B^0 \rightarrow K^{*0} \bar{K}^{*0}$ , should exhibit similar  $R_L \approx 0.6$ . The comparison among the different proposals for resolving the puzzle has been summarized in Table 3, which can be discriminated experimentally in the near future.

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## References

- [1] H-n. Li and S. Mishima, Phys. Rev. D **71**, 054025 (2005).
- [2] S. Eidelman *et al.* [Particle Data Group Collaboration], Phys. Lett. B **592**, 1 (2004).
- [3] T. Aushev, Belle-conf-0453, talk presented at the 32nd International Conference on High Energy Physics, Aug. 16-22, 2004, Beijing, China.
- [4] J. Zhang *et al.* [BELLE Collaboration], Phys. Rev. Lett. **91**, 221801 (2003).

- [5] B. Aubert *et al.* [BABAR Collaboration], hep-ex/0409059.
- [6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **71**, 031103 (2005).
- [7] C.H. Chen, Y.Y. Keum, and H-n. Li, Phys. Rev. D **66**, 054013 (2002).
- [8] J. Zhang, *et al.* [BELLE Collaboration], hep-ex/0408141.
- [9] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **91**, 171802 (2003).
- [10] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **93**, 231804 (2004).
- [11] K. Abe *et al.* [Belle Collaboration], hep-ex/0408102.
- [12] B. Aubert *et al.* [BABAR Collaboration], hep-ex/0408093.
- [13] Y. Grossman, hep-ph/0310229.
- [14] Y.D. Yang, R.M. Wang, and G.R. Lu, hep-ph/0411211.
- [15] A.L. Kagan, Phys. Lett. B **601**, 151 (2004); hep-ph/0407076.
- [16] M. Beneke, G. Buchalla, M. Neubert, and C.T. Sachrajda, Phys. Rev. Lett. **83**, 1914 (1999); Nucl. Phys. **B591**, 313 (2000); Nucl. Phys. **B606**, 245 (2001).
- [17] C.W. Bauer, D. Pirjol, I.Z. Rothstein, and I.W. Stewart, Phys. Rev. D **70**, 054015 (2004).
- [18] P. Colangelo, F. De Fazio, and T.N. Pham, Phys. Lett. B **597**, 291 (2004).
- [19] M. Ladisa, V. Laporta, G. Nardulli, and P. Santorelli, Phys. Rev. D **70**, 114025 (2004).
- [20] H.Y. Cheng, C.K. Chua, and A. Soni, Phys. Rev. D **71**, 014030 (2005).
- [21] W.S. Hou and M. Nagashima, hep-ph/0408007.
- [22] H-n. Li, hep-ph/0408232; JKPS **45**, 397 (2004).
- [23] M. Beneke, G. Buchalla, M. Neubert, and C.T. Sachrajda, hep-ph/0411171.
- [24] L. Wolfenstein, hep-ph/0407344.
- [25] Z. Ligeti, hep-ph/0408267.
- [26] H-n. Li and H.L. Yu, Phys. Rev. Lett. **74**, 4388 (1995); Phys. Lett. B **353**, 301 (1995); Phys. Rev. D **53**, 2480 (1996).
- [27] Y.Y. Keum, H-n. Li, and A.I. Sanda, Phys. Lett. B **504**, 6 (2001); Phys. Rev. D **63**, 054008 (2001); Y.Y. Keum and H-n. Li, Phys. Rev. **D63**, 074006 (2001).
- [28] C.D. Lü, K. Ukai, and M. Z. Yang, Phys. Rev. D **63**, 074009 (2001).
- [29] M. Bauer, B. Stech, M. Wirbel, Z. Phys. C **29**, 637 (1985); *ibid.* **34**, 103 (1987).



- [30] C.H. Chen and H-n. Li, Phys. Rev. D **63**, 014003 (2001).
- [31] M. Beneke and T. Feldmann, Nucl. Phys. **B592**, 3 (2000).
- [32] J. Charles *et al.*, Phys. Rev. D **60**, 014001 (1999).
- [33] A. Ali and A.Y. Parkhomenko, Eur. Phys. J. C **23**, 89 (2002); A. Ali, hep-ph/0210183.
- [34] M. Beneke, T. Feldmann, and D. Seidel, Nucl. Phys. **B612**, 25 (2001).
- [35] D. Becirevic, hep-ph/0211340.
- [36] <http://www.slac.stanford.edu/xorg/hfag>.
- [37] H.Y. Cheng and K.C. Yang, Phys. Lett. B **511**, 40 (2001).
- [38] P. Ball, V.M. Braun, Y. Koike, and K. Tanaka, Nucl. Phys. **B529**, 323 (1998).
- [39] V.M. Braun and A. Lenz, Phys. Rev. D **70**, 074020 (2004).
- [40] H.Y. Cheng, C.K. Chua, and C.W. Hwang, Phys. Rev. D **69**, 074025 (2004) and references therein; H.Y. Cheng, hep-ph/0410316.
- [41] T. Kurimoto, H-n. Li and A.I. Sanda, Phys. Rev. D **65**, 014007 (2002).
- [42] C.H. Chen, Y.Y. Keum, and H-n. Li, Phys. Rev. D **64**, 112002 (2001).
- [43] C.D. Lü and M.Z. Yang, Eur. Phys. J. C **23**, 275 (2002).
- [44] A. Kagan, private communication; talk presented at the 6th Workshop on a Higher Luminosity B Factory, Nov. 16-18, 2004, KEK, Tsukuba, Japan.